

The orbital period evolution of the supersoft X-ray source CAL 87

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ABSTRACT

CAL 87 is one of the best known supersoft X-ray sources. However, the measured masses, orbital period and orbital period evolution of CAL 87 cannot be addressed by the standard thermal-timescale mass-transfer model for supersoft X-ray sources. In this work we explore the orbital evolution of CAL 87 with both analytic and numerical methods. We demonstrate that the characteristics mentioned above can be naturally accounted for by the excited-wind-driven mass-transfer model.

Subject headings: binaries: close – stars: evolution – white dwarfs – stars: neutron – X-rays: binaries

1. Introduction

Supersoft X-ray sources (SSSs) are characterized by black body-like spectra with temperatures $\sim 20\text{--}100\text{ eV}$ and X-ray luminosities $\sim 10^{35}\text{--}10^{38}\text{ erg s}^{-1}$ (Greiner 1996). van den Heuvel et al. (1992) suggested that the supersoft X-ray emission stems from stable nuclear burning on the surface of white dwarfs (WDs), which requires a high mass transfer ($\gtrsim 10^{-7} M_{\odot} \text{ yr}^{-1}$) from the donor star in an interacting binary. This leading scenario then involves mass transfer, which is unstable on a thermal timescale, from a more massive main-sequence (MS) or subgiant donor star (see Kahabka & van den Heuvel 1997, for a review).

CAL 87 is a well known SSS in the Large Magellanic Cloud (Cowley et al. 1990; Hutchings et al. 1998) with X-ray luminosity $\sim 4 \times 10^{36} \text{ erg s}^{-1}$ (Starrfield et al. 2004). It is a close binary with orbital period of $P_{\text{orb}} = 10.6\text{ hr}$ (Alcock et al. 1997). The WD is very massive with mass $\sim 1.35 M_{\odot}$ (Starrfield et al. 2004), but the donor mass ($\sim 0.34 M_{\odot}$) is quite low

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(Oliveira & Steiner 2007). Moreover, Oliveira & Steiner (2007) showed that the orbital period of CAL 87 was increasing at a rate of $\dot{P}_{\text{orb}} = 7.2(\pm 1.3) \times 10^{-10} \text{ ss}^{-1}$. A more recent analysis by Ribeiro et al. (2014) refined the value of \dot{P}_{orb} to be $6(\pm 2) \times 10^{-10} \text{ ss}^{-1}$. CAL 87 is thought to be the prototype of SSSs which predicts a decreasing orbital period, but both the small mass ratio and the expanding orbit do not fit the standard picture of SSSs.

van Teeseling & King (1998) and King & van Teeseling (1998) have alternatively proposed a self-excited wind model for SSSs. In this model, the companion star is irradiated by the soft X-rays from the SSS, exciting strong winds that drive Roche-lobe overflow (RLOF) at a high rate to sustain steady hydrogen burning on the accreting WD, even when the companion star is less massive than the WD. In the binaries with $M_2/M_1 < 1$, the wind-driven process is expected to be triggered by: (1) a long phase of residual hydrogen burning after a mild shell flash, (2) a late helium shell flash of the cooling white dwarf, after the system has already come into contact as a cataclysmic variable (King & van Teeseling 1998). In this work, we will examine whether this wind-driven mass transfer model can explain the orbital evolution of CAL 87. We present an analytical derivation of the mass-transfer rate in section 2 and numerical calculations of this rate in section 3. The results are summarized in section 4.

2. Analytical Method

The total orbital angular momentum of a binary is give by

$$J = \mu(GMa)^{1/2} = G^{2/3}M^{2/3}\left(\frac{P_{\text{orb}}}{2\pi}\right)^{1/3}, \quad (1)$$

where $\mu = M_1M_2/M$ is the reduced mass, $M = M_1 + M_2$ is the total mass (M_1 and M_2 are the masses of the WD the donor star, respectively), and a is the binary separation. From Eq. (1) the rate of change of the orbital angular momentum can be derived to be,

$$\frac{\dot{J}}{J} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{3}\frac{\dot{M}}{M} + \frac{1}{3}\frac{\dot{P}_{\text{orb}}}{P_{\text{orb}}}. \quad (2)$$

Mass loss from the donor star is composed by two parts,

$$\dot{M}_2 = \dot{M}_{2\text{tr}} + \dot{M}_{2\text{w}}, \quad (3)$$

where $\dot{M}_{2\text{tr}}$ is the mass transfer rate through RLOF, and $\dot{M}_{2\text{w}}$ is the excited wind loss rate from the donor star. Only part of the transferred material from the donor star can be used to increase the WD mass. The mass growth rate of the WD is,

$$\dot{M}_1 = \alpha_{\text{H}}\alpha_{\text{He}}|\dot{M}_{2\text{tr}}|, \quad (4)$$

where α_{H} and α_{He} are the accumulation ratios for hydrogen and helium burning, respectively. The excess material is assumed to be ejected from the surface of the WD. The total mass loss rate is then,

$$\dot{M} = (1 - \alpha_{\text{H}}\alpha_{\text{He}})\dot{M}_{2\text{tr}} + \dot{M}_{2\text{w}}. \quad (5)$$

Thus the rate of angular momentum loss caused by the mass loss from the WD and the donor star is

$$\dot{J}_{\text{ML}} = (1 - \alpha_{\text{H}}\alpha_{\text{He}})\dot{M}_{2\text{tr}}a_1^2\omega + \dot{M}_{2\text{w}}a_2^2\omega \quad (6)$$

where $a_1 = (\frac{M_2}{M})a$ and $a_2 = (\frac{M_1}{M})a$ are the distances between the WD and the center of mass, and between the donor star and the center of mass, respectively, $\omega = 2\pi/P_{\text{orb}}$ is the orbital angular velocity.

For angular momentum loss caused by magnetic braking (MB) we adopt the saturated law proposed by Andronov et al. (2003) and Sills et al. (2000)

$$\dot{J}_{\text{MB}} = \begin{cases} -K\omega^3 \left(\frac{R_2}{R_{\odot}}\right)^{1/2} \left(\frac{M_2}{M_{\odot}}\right)^{-1/2}, & \text{if } \omega \leq \omega_{\text{crit}}, \\ -K\omega_{\text{crit}}^2\omega \left(\frac{R_2}{R_{\odot}}\right)^{1/2} \left(\frac{M_2}{M_{\odot}}\right)^{-1/2}, & \text{if } \omega > \omega_{\text{crit}}, \end{cases} \quad (7)$$

where $K = 2.7 \times 10^{47} \text{ gcm}^2 \text{ s}$, and ω_{crit} is the critical angular velocity at which the angular momentum loss rate reaches a saturated state.

Combining Eqs. (2)-(7) we get for the rate of change of the orbital period :

$$\frac{\dot{P}_{\text{orb}}}{P_{\text{orb}}} = -\frac{[3M_1^2 + 2(1 - \alpha_{\text{H}}\alpha_{\text{He}})M_1M_2 - 3M_2^2]\dot{M}_{2\text{tr}} + 2M_1M_2\dot{M}_{2\text{w}}}{M_1M_2M} + 3\frac{\dot{J}_{\text{MB}}}{J}. \quad (8)$$

As an order of magnitude estimate, if we take the parameters of CAL 87 (i.e., $M_1 = 1.35M_{\odot}$, $M_2 = 0.34M_{\odot}$, and $P_{\text{orb}} = 10.6 \text{ hr}$) and assume $\dot{M}_{2\text{w}} \simeq \dot{M}_{2\text{tr}} \simeq -1 \times 10^{-7}M_{\odot} \text{ yr}^{-1}$, $\alpha_{\text{H}}\alpha_{\text{He}} \sim 0.5$, then we obtain $\dot{P}_{\text{orb}} \sim 9.98 \times 10^{-10} \text{ ss}^{-1}$, roughly consistent with the observed value.

Figure 1 shows how for the above-adopted masses & orbital period \dot{P}_{orb} depends on the mass-transfer rate (left panel) and for $M_1 = 1.35M_{\odot}$ how it depends on the mass ratio $q = M_2/M_1$ (right panel) with $\alpha_{\text{H}}\alpha_{\text{He}} = 0.5$. In the left panel it is seen that the orbital period increases when $\dot{M}_{\text{tr}} > 2 \times 10^{-8} M_{\odot}\text{yr}^{-1}$, and \dot{P}_{orb} increases with increasing mass-transfer rate. In the right panel we adopt $M_1 = 1.35M_{\odot}$ and $\dot{M}_{2\text{w}} = \dot{M}_{2\text{tr}} = -1 \times 10^{-7}M_{\odot} \text{ yr}^{-1}$. One observes that the orbital period always increases when $q < 1$, and \dot{P}_{orb} decreases with increasing q .

3. Numerical calculation

van Teeseling & King (1998) and King & van Teeseling (1998) suggested that the soft X-ray radiation from an accreting WD may heat the donor star and produce a strong stellar wind from the heated side of the donor star. If the wind carries away the specific angular momentum of the donor star, mass transfer will be driven at a rate comparable with the wind loss rate. The relation between the mass transfer rate \dot{M}_{tr} and the wind loss rate \dot{M}_{w} obeys

$$\dot{M}_{\text{w}} \simeq (3.5 \times 10^{-7} M_{\odot} \text{ yr}^{-1}) \left(\frac{M_2}{M_{\odot}} \right)^{5/6} \left(\frac{M}{M_{\odot}} \right)^{-1/3} (\eta_{\text{s}} \eta_{\text{a}})^{1/2} \phi \left(\frac{\dot{M}_{\text{tr}}}{10^{-7} M_{\odot} \text{ yr}^{-1}} \right)^{1/2}, \quad (9)$$

for $M_2 \lesssim M_1$; and

$$\dot{M}_{\text{w}} \simeq (3.5 \times 10^{-7} M_{\odot} \text{ yr}^{-1}) \left(\frac{M_2}{M_{\odot}} \right)^{0.95} \left(\frac{M}{M_{\odot}} \right)^{-1/3} \left(\frac{M_1}{M_{\odot}} \right)^{-0.12} (\eta_{\text{s}} \eta_{\text{a}})^{1/2} \phi \left(\frac{\dot{M}_{\text{tr}}}{10^{-7} M_{\odot} \text{ yr}^{-1}} \right)^{1/2}, \quad (10)$$

for $M_2 \gtrsim M_1$. Here η_{s} is the efficiency of the WD’s spectrum in producing ionizing photons normalized to the case of supersoft X-ray temperatures of about 10^5 K, η_{a} measures the luminosity per gram of matter accreted relative to the value for H shell burning, and ϕ parameterizes the fraction of the donor’s irradiated face and the fraction of the wind mass escaping the system.

Taking into account the occurrence of irradiation-excited winds and their influence on the binary evolution, we investigate the mass transfer processes of a binary consisting of a CO WD and a MS companion star with an updated version of Eggleton’s stellar evolution code (Eggleton 1971, 1973). In addition, angular momentum loss caused by gravitational wave radiation (Landau & Lifshitz 1975) and MB (Andronov et al. 2003; Sills et al. 2000) is also included in the calculation. The growth of the WD mass depends on the accumulation efficiencies of hydrogen- and helium-rich matter. Here we adopt the results of Prialnik & Kovetz (1995) and Yaron et al. (2005) for the α_{H} , and the prescriptions in Kato & Hachisu (2004) for α_{He} .

We have performed numerical calculations of the evolution for a grid of binaries. To illustrate the possible formation history of CAL 87, we consider a binary consisting of a CO WD of initial mass $1.16 M_{\odot}$ and a MS companion star of initial mass $1.1 M_{\odot}$ with an initial orbital period 0.3 day. The detailed calculated results are as follows.

Figure 2 shows the RLOF mass-transfer rate (the black line) and the wind loss rate (the red line) as a function of time. Although less massive than the WD, the companion star is able to transfer mass to the WD material at a high enough rate ($\gtrsim 10^{-7} M_{\odot} \text{ yr}^{-1}$), with the help of the excited wind. In Figure 3, we plot the evolution of the donor’s mass

(black dashed line) and the WD’s mass (red dotted line). The WD can finally grow in mass up to the Chandrasekhar limit mass and explode as a supernova Ia. Figure 4 shows the evolution of the orbital period (left) and its derivative (right). Initially MB-induced angular momentum loss causes the orbit to shrink. When the excited wind loss is sufficiently strong, it starts to dominate the orbital evolution. Rapid mass transfer and mass loss cause the orbit to expand with time. At the time $t \sim 4 \times 10^6$ yr (or $\log t$ (yr) ~ 6.6), both the orbital period and its derivative are in agreement with observed values indicated by red dashed lines.

4. Concluding remarks

Ribeiro et al. (2014) derived a rate $\dot{P}_{\text{orb}} = 6(\pm 2) \times 10^{-10}$ for the change in the orbital period of CAL 87 from its eclipse maps. In this paper, we employ both analytical and numerical methods to show that the excited wind-driven mass transfer model (van Teeseling & King 1998; King & van Teeseling 1998) is able to reproduce observed characteristics of CAL 87. Other evidence supporting this model comes from the fact that there is no significant variation of the emission lines of CAL 87 even during eclipses, suggesting that the lines are formed in an extended region a circumbinary corona, which could be fed by winds from both the disk and the donor star (Ribeiro et al. 2014).

Ribeiro et al. (2014) also mentioned that CAL 87 actually displayed cyclic orbital period changes, with \dot{P}_{orb} changing from positive to negative value of $-2.2(\pm 0.2) \times 10^{-10}$, and they speculated that the latter may be induced by MB coupled with strong winds. This would require a very strong magnetic field for the donor star: the negative value of the observed \dot{P}_{orb} can be accounted for if we amplify the traditional MB-induced \dot{J} by a factor of ~ 240 . An alternative explanation is that mass loss during the shell burning flashes may decrease the orbital period. Assuming that during the flashes a fraction δ of the accreted matter escapes from the binary system through the outer Lagrangian (L_3) point, then the angular momentum loss rate is,

$$\frac{\dot{J}_{L_3}}{J} = -\delta \frac{a_{L_3}^2}{a^2} \frac{M}{M_1} \frac{\dot{M}_{2\text{tr}}}{M_2} \quad (11)$$

where a_{L_3} is the distance between the mass center of the binary and the L_3 point. Taking $\delta \sim 0.15 - 0.45$ (Shao & Li 2012), we find that when the mass-transfer rate is $\gtrsim 4 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$, the escaping matter may shrink the orbit at a rate comparable with observed.

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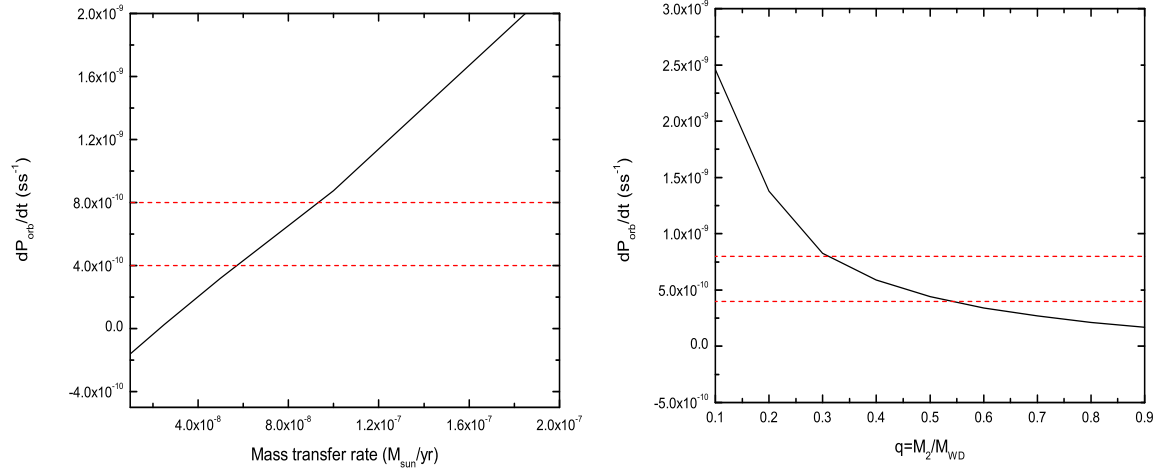


Fig. 1.— Dependence of \dot{P}_{orb} on the mass transfer rate and the mass ratio. The red dashed lines represent the observed values of CAL 87.

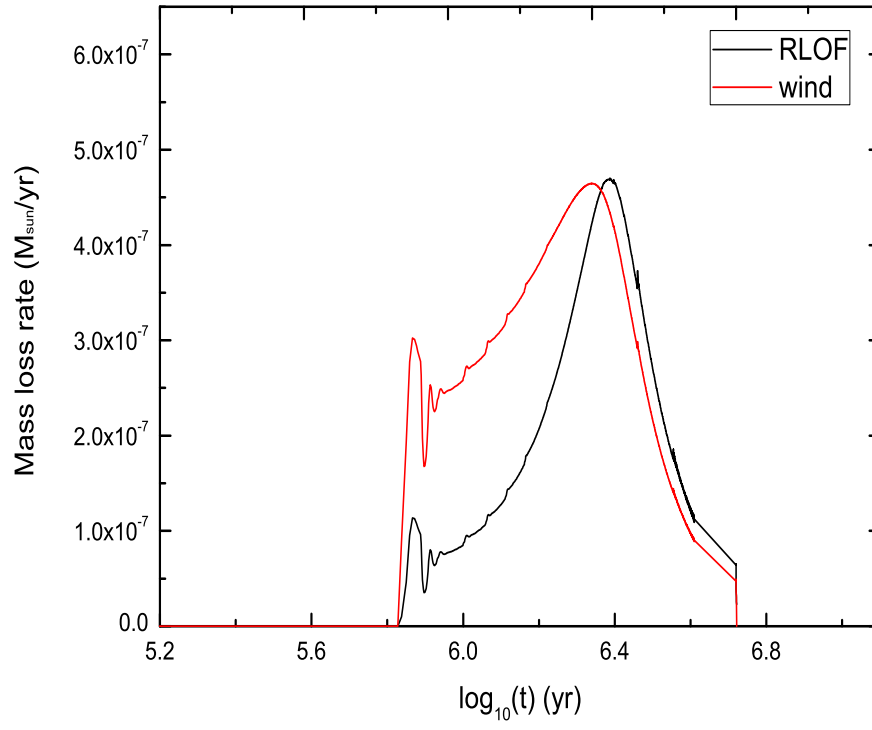


Fig. 2.— Evolution of the RLOF mass-transfer rate (black line) and the excited wind loss rate (red line).

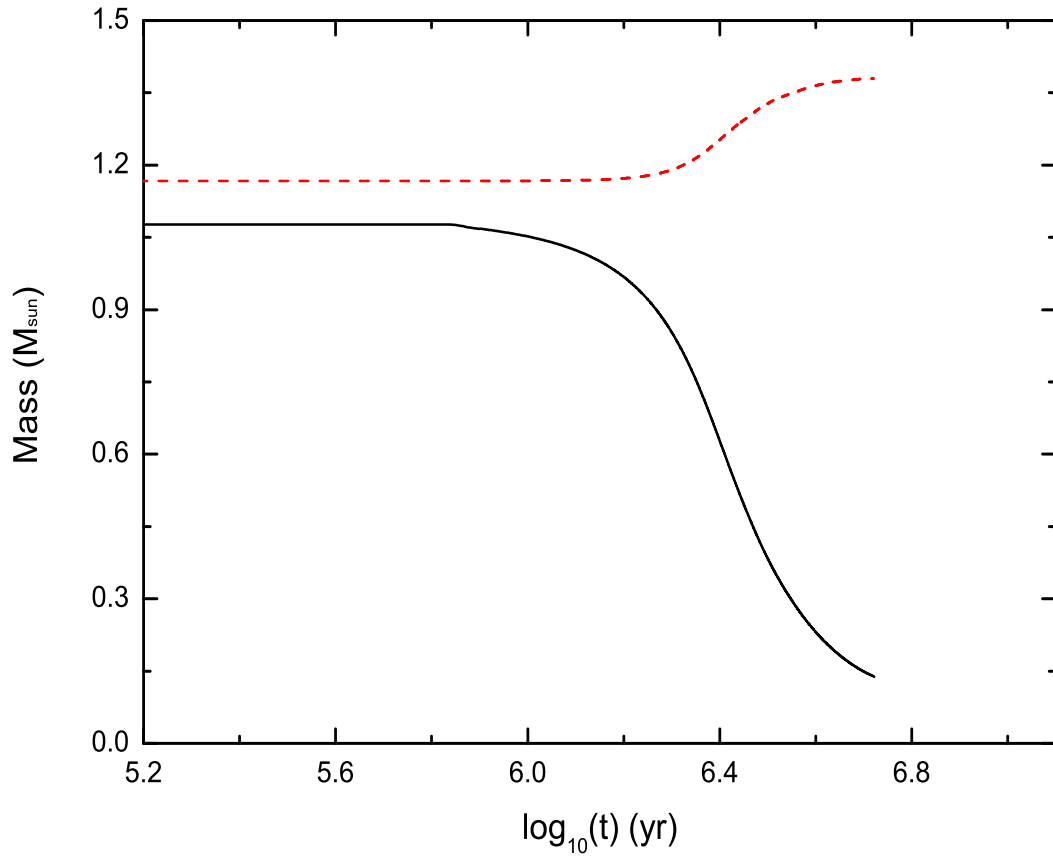


Fig. 3.— Evolution of the donor's mass (black line) and the WD mass (red line).

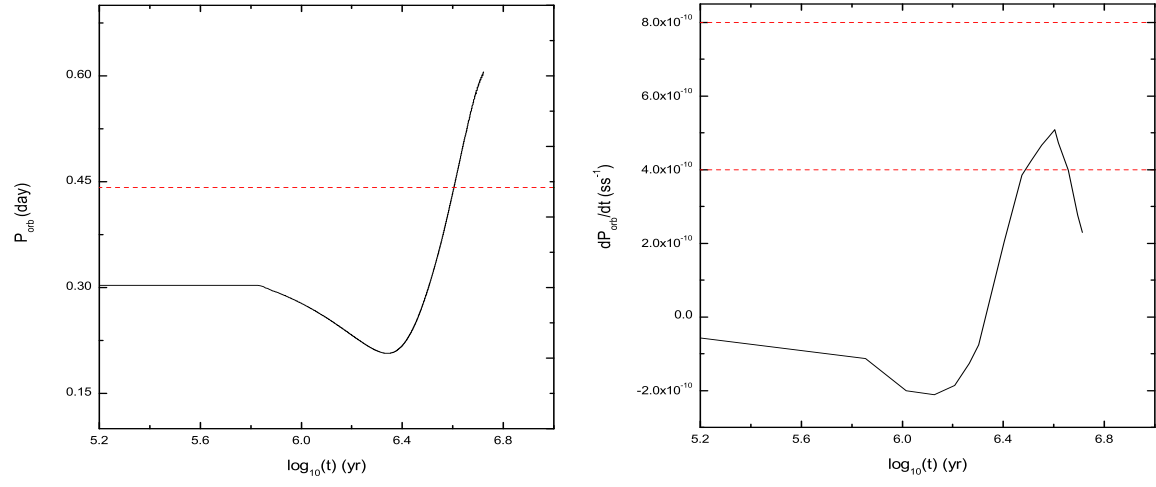


Fig. 4.— Evolution of the orbital period (left) and its derivative (right).